

Evaluation of sex estimation through mandibular morphometric measurements on cone-beam computed tomography images

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ABSTRACT

Aims: Sex estimation of unidentified human remains is a critical component of forensic investigations. Among facial bones, the mandible is the most robust and resilient structure, making it a valuable element for personal identification. The aim of this study was to evaluate the potential of mandibular metric parameters-obtained via cone-beam computed tomography (CBCT)-for determining sex.

Methods: CBCT scans of 199 individuals (72 males and 127 females), aged between 18 and 81 years, were retrospectively analyzed. Nine mandibular parameters were measured including the mandibular angle, coronoid and condylar lengths, minimal ramus breadth, and mandibular length, along with bigonial breadth, bicondylar breadth, bimental breadth, and symphyseal height. Statistical analyses included repeated measures ANOVA, independent samples t-test, Pearson correlation, and discriminant function analysis.

Results: Males consistently exhibited higher mean values across all parameters, except for the mandibular angle, which was slightly greater in females (female: 119.33 ± 0.56 ; male: 118.79 ± 0.75) but not statistically significant ($p=0.566$). The most influential variables, based on structure matrix coefficients, were left coronoid length (0.791), right coronoid length (0.649), left condylar length (0.492), and bigonial breadth (0.477). Discriminant function analysis yielded a high overall sex classification accuracy of 91.5%.

Conclusion: The mandible demonstrated high discriminative power, with CBCT-derived measurements providing accurate and reproducible indicators of sexual dimorphism. These findings underscore the utility of mandibular morphometry as a reliable tool for sex estimation in forensic practice.

Keywords: Forensic sciences, cone beam computed tomography, sex determination by skeleton, anthropometry

INTRODUCTION

In recent years, there has been an increase in the number of unidentified human remains worldwide due to various disasters, including fires, plane crashes, natural calamities, building collapses, traffic accidents, homicides, and terrorist attacks. Therefore, establishing the identity of a deceased individual is crucial from legal, criminal, and ethical perspectives.¹ Personal identification requires interdisciplinary knowledge and expertise, particularly in fields such as anatomy, radiology, archaeology, and dentistry. The first and most essential step in the identification process is sex determination, as it immediately eliminates approximately half of the population and provides the basis for further estimations of age and stature using sex-specific standards.^{2,3}

Sexual dimorphism plays a critical role in narrowing down identity by guiding the identification process toward a more accurate conclusion. Traditionally, bones such as the pelvis, skull, and long bones have been used for sex determination.

Among these, the skull is considered the most sexually dimorphic structure after the pelvis. Since craniofacial structures are predominantly composed of hard tissues, they are highly valuable in sex estimation.¹ The mandible, as one of the most robust, largest, and morphologically variable bones of the skull, is particularly useful. Its dense cortical bone structure provides exceptional preservation against trauma, making it an ideal candidate for forensic analysis. Sexual dimorphism in the mandible is primarily reflected in its size and shape, with male mandibles generally being larger and more robust than those of females.^{1,4-6}

Previous osteometric studies have employed both dry bones and radiographic images for sex estimation. Cone-beam computed tomography (CBCT) has been shown to provide higher accuracy, reproducibility, and reliability compared to conventional methods. CBCT produces high-resolution, undistorted three-dimensional images with relatively low

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radiation exposure and is non-invasive, preserving the integrity of the examined tissues.^{5,7,8} Several studies have assessed sexually dimorphic mandibular morphometric parameters such as mandibular angle, ramus height, minimal ramus breadth, bigonial breadth, and bicondylar breadth using CBCT images.^{4,5,9} In addition to using measurement values, landmarks plotting on the 3D model surfaces of the mandible has been reported in the literature for sex estimation.^{10,11} At the same time, a growing body of research has explored Artificial Intelligence (AI) methods, including machine learning algorithms,^{12,13} convolutional neural networks (CNNs),¹⁴ and multi-task learning frameworks,¹⁵ which further emphasize the future potential of automated forensic identification systems.

The aim of the present study was to evaluate mandibular metric parameters obtained from CBCT images in a Turkish subpopulation and to determine their predictive accuracy for sex estimation. Unlike many previous studies, it uses a relatively large sample size and multiple bilateral parameters to provide robust discriminant models applicable to forensic identification. The hypothesis of the study is that CBCT-derived mandibular measurements would exhibit significant sexual dimorphism and that a discriminant function based on these parameters would yield high accuracy in sex classification.

METHODS

This retrospective study was conducted using CBCT images obtained between 2016 and 2024 at the Department of Oral and Maxillofacial Radiology, Faculty of Dentistry, Süleyman Demirel University. Ethical approval was granted by the Süleyman Demirel University Health Sciences Ethics Committee (Date: 04.07.2025, Decision No: 35). All procedures were carried out in accordance with the ethical rules and the principles of the Declaration of Helsinki. A total of 238 CBCT scans taken for various clinical indications were initially screened. All CBCT examinations were performed on the same device (Planmeca ProMax 3D Mid, Helsinki, Finland) under standardized acquisition parameters, with a 20×10 cm field of view and a voxel size of 0.4 mm. After applying inclusion and exclusion criteria, 199 healthy individuals were included in the study. Individuals aged 18 years or older with complete visualization of the mandible within the field of view were considered eligible.

Subjects with a history of congenital anomalies, trauma, tumors, or surgical interventions involving the jawbones were excluded. A priori power analysis was performed using G*power software (version 3.1.9.4, University of Düsseldorf, Germany). Assuming a medium effect size (Cohen’s d=0.5), with a significance level of 0.05 and a statistical power of 80%, the minimum required sample size was calculated as 66 participants. Demographic data was retrieved from the institutional Picture Archiving and Communication System (PACS). CBCT images were obtained from Romexis software version 3.8.3 (Planmeca, Helsinki, Finland). Mandibular linear and angle measurements were performed using QuickVision 3D software. Anatomical landmarks were localized on three dimensional reconstructions and confirmed in axial, coronal and sagittal planes. A single trained investigator performed all measurements to avoid inter-observer variability. For reliability assessment, 40 CBCT scans were re-evaluated, and intraclass correlation coefficients (ICC) were calculated. Definitions, references, and measurement planes for each mandibular parameter are summarized in Table 1, with sample CBCT representations shown in Figure 1 and 2.

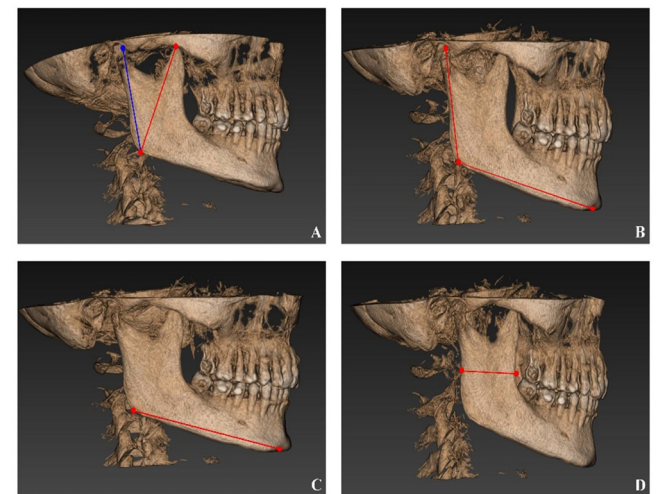


Figure 1. Representative CBCT three-dimensional reconstructions (lateral view) demonstrating the linear and angular measurements performed in the study. (A) Coronoid length (blue line), defined as the distance between the coronoid process tip and gonion; and condylar length (red line), defined as the distance between condylion and gonion. (B) Mandibular angle, measured as the angle formed between the condylion-gonion and menton-gonion lines. (C) Mandibular length, measured as the linear distance from menton to gonion. (D) Minimum ramus breadth, defined as the narrowest width of the mandibular ramus in the sagittal view
CBCT: Cone-beam computed tomography

Table 1. Definitions, references, and cone beam computed tomography reconstruction planes used for the measurement of mandibular parameters			
Parameter	Definition	Measurement plane	Reference
Coronoid length	Distance between the coronoid and gonion points	Sagittal view	Assari et al., ⁵
Condylar length	Distance between the condylion and gonion points	Sagittal view	Assari et al., ⁵
Mandibular length	Distance between the menton and gonion points	Sagittal view	Assari et al., ⁵
Mandibular angle	Angle between condylion-gonion and menton -gonion lines	Sagittal view	Assari et al., ⁵
Minimum ramus breadth	Narrowest width of the mandibuar ramus	Sagittal view	Kallalli et al., ⁴
Bigonial breadth	Distance between the right and left gonion points	Axial view	Kallalli et al., ⁴
Bicondylar breadth	Distance between the most lateral points of the condyles	Axial view	Kallalli et al., ⁴
Bimental breadth	Distance between the mental foramina	Coronal view	Kumar and Lokanadham, ¹⁶
Symphyseal height	Distance from the alveolar crest of the mandibular central incisors to the inferior mandibular border	Coronal view	Direk et al. ¹⁷

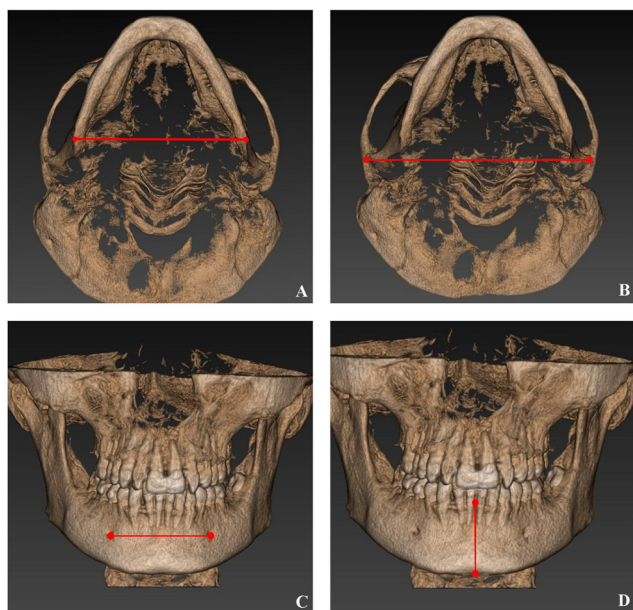


Figure 2. Representative CBCT three-dimensional reconstructions (axial and coronal views) illustrating transverse and vertical mandibular measurements. (A) Bigonial breadth, defined as the distance between the right and left gonion points. (B) Bicondylar breadth, defined as the distance between the most lateral points of the mandibular condyles. (C) Bimental breadth, measured as the linear distance between the right and left mental foramina. (D) Symphysis height, measured as the vertical distance from the alveolar crest of the mandibular central incisors to the most inferior point of the mandibular symphysis

CBCT: Cone-beam computed tomography

Statistical Analysis

All analyses were performed using SPSS software (version 26.0; IBM Corp., Armonk, NY). Categorical variables were expressed as frequencies and percentages, and continuous variables as means and standard deviations. The normality of continuous variables was assessed using the Kolmogorov-Smirnov test. A general linear model (GLM) with repeated measures was used to evaluate side (right vs. left) and sex effects on bilateral measurements. Independent samples T tests were used to compare unpaired variables between sexes. Pearson correlation analysis was conducted to assess associations between age and mandibular measurements. Discriminant function analysis was performed to determine which combination of measurements best predicts sex classification.

RESULTS

CBCT images of 199 individuals (72 males and 127 females) were evaluated. The mean age was 32.96 ± 14.66 with minimum 18 and maximum 81 years old individuals. .

Male participants exhibited significantly greater mean values for condylar length ($p=0.035$), minimal ramus breadth ($p=0.001$), mandibular length ($p<0.001$), and coronoid length ($p<0.001$) compared to females (Table 2). The effect of side (right vs. left) was not significant for bilateral measurements ($p>0.05$), except for coronoid length ($p=0.017$).

Males demonstrated significantly higher values for bigonial breadth, bicondylar breadth, bimental breadth, and symphyseal height ($p<0.001$), whereas mandibular angles did not differ significantly between sexes ($p>0.05$) (Table 2).

Table 2. Comparison of the measurements of mandible according to sex

	Male, mean $\pm$ SD	Female, mean $\pm$ SD	p
Condylar length	68.76 $\pm$ 3.57	59.27 $\pm$ 2.69	0.035
Coronoid length	63.79 $\pm$ 0.52	55.85 $\pm$ 0.39	<0.001
Mandibular length	77.55 $\pm$ 0.74	73.86 $\pm$ 0.56	<0.001
Minimal ramus breadth	29.95 $\pm$ 0.37	28.36 $\pm$ 0.28	0.001
Mandibular angle	118.79 $\pm$ 0.75	119.33 $\pm$ 0.56	0.566
Bicondylar breadth	113.36 $\pm$ 10.84	104.95 $\pm$ 8.42	<0.001
Bigonial breadth	96.72 $\pm$ 8.42	89.31 $\pm$ 5.32	<0.001
Bimental breadth	46.39 $\pm$ 3.30	43.89 $\pm$ 3.06	<0.001
Symphyseal height	30.76 $\pm$ 4.10	26.92 $\pm$ 3.58	<0.001

SD: Standard deviation

Pearson correlation analysis revealed significant associations between age and right mandibular length ($r=0.204$; $p=0.004$), left mandibular length ($r=0.142$; $p=0.046$), bicondylar breadth ($r=-0.224$; $p=0.002$), and symphyseal height ($r=-0.290$; $p<0.001$).

Discriminant function analysis was conducted to determine whether mandibular measurements could accurately predict sex. The analysis produced one significant canonical discriminant function with a canonical correlation of 0.751 and Wilks' Lambda of 0.436 ($\chi^2(14)=157.58$, $p<0.001$), explaining 100% of the variance.

The most influential variables based on structure matrix coefficients were left coronoid length (0.791), right coronoid length (0.649), left condylar length (0.492), and bigonial breadth (0.477) (Table 3). The classification accuracy was 89.9% for original grouped cases, indicating a high level of predictive validity. In the classification matrix, 7 males (9.7%) were misclassified as females, and 10 females (7.9%) were misclassified as males, resulting in an overall accuracy of 91.5%. Cross-validated classification yielded 89.4% correct predictions. In stepwise discriminant analysis, 89.9% of original grouped cases correctly classified with was used left condylar length, left mandibular length, left coronoid length, left mandibular angle, bicondylar breadth, bigonial breadth parameters (Table 4).

Table 3. Fisher's linear discriminant functions for sex classification based on mandibular morphometric measurements

Parameter	Function
Coronoid length (left)	0.791
Coronoid length (right)	0.649
Condylar length (left)	0.492
Bigonial breadth	0.477
Symphyseal height	0.433
Bicondylar breadth	0.381
Bimental breadth	0.337
Mandibular length (left)	0.240
Mandibular length (right)	0.232
Minimal ramus breadth (right)	0.221
Minimal ramus breadth (left)	0.181
Condylar length (right)	0.085
Mandibular angle (left)	-0.040
Mandibular angle (right)	-0.028

Table 4. Discriminant analysis of sex using mandibular morphometric parameters

		Predicted group membership		
	Sex	Male [n (%)]	Female [n (%)]	Total, n
Original	Male	65 (90.3)	7 (9.7)	72
	Female	10 (7.9)	117 (92.1)	127
Cross-validated	Male	64 (88.9)	8 (11.1)	72
	Female	13 (10.2)	114 (89.8)	127

The ICC was calculated as 0.986, which reflects excellent intra-observer agreement and further strengthens the validity of the study findings.

DISCUSSION

Sex estimation is a fundamental aspect of forensic identification, especially in cases involving fragmented, incomplete, or severely decomposed remains. The mandible, as the strongest and most durable bone of the craniofacial complex, offers critical morphometric indicators that can be employed in the absence of more complete skeletal structures.¹⁸

In this study, mandibular morphology was evaluated using CBCT in a Turkish adult population. Our findings revealed statistically significant sexual dimorphism in several mandibular parameters, including condylar and coronoid lengths, mandibular length, minimal ramus breadth, and transverse dimensions such as bigonial and bicondylar breadths. In contrast, mandibular angle did not differ significantly between sexes, with females displaying slightly higher values-consistent with previous studies conducted in Turkish populations.^{9,19} The discriminant function analysis yielded a remarkable classification accuracy of 91.5%, with left coronoid length, left condylar length, and bigonial breadth emerging as the most influential predictors. Misclassifications were relatively balanced between sexes (9.7% in males vs. 7.9% in females), indicating that the model did not exhibit sex-related bias. Errors were mostly observed in cases with borderline values of mandibular length and bicondylar breadth, where partial overlap between male and female measurements may have contributed to reduced discriminability.

It is well established that skeletal characteristics vary across populations.⁷ Kharoshah et al.²⁰ reported an 83.9% classification accuracy in an Egyptian sample based on bicondylar breadth, mandibular angle, minimum ramus breadth, and ramus length. In Northeast China, Zheng et al.²¹ reported an overall accuracy of 87.4% using CBCT measurements. Similarly, Dong et al.²² demonstrated predictive accuracies ranging from 80.5% to 84.2% across various multivariate models in a Chinese sample, with bicondylar breadth showing pronounced dimorphism. de Oliveira Gamba et al.²³ achieved 95.1% correct classification in a Brazilian population using parameters such as ramus length, gonion-gnathion length, and bigonial breadth. Alias et al.²⁴ reported an overall classification accuracy of 78.5%, identifying bigonial breadth and condylar height as the strongest discriminators. Conversely, Kano et al.,²⁵ in a Japanese population, did not find significant sexual dimorphism in gnathion-condyle distances or bicondylar breadth. These different results reveal

the impact of population-specific variation and highlight the importance of developing population-specific discriminant models.

The discrepancies among populations regarding the sexual dimorphism of the mandible may be attributed to several factors. Genetic and ethnic variability is an important determinant of craniofacial morphology, leading to population-specific patterns.^{26,27} Environmental and functional factors such as stressful lifestyle and dietary habits can also influence mandible development and measurements.^{28,29} In our sample, the absence of significant dimorphism in the mandibular angle, along with slightly higher values in females, suggests that population-specific skeletal characteristics and age-related remodeling may have contributed to this result.

Several studies in the Turkish population have investigated sex prediction using mandibular and cranial measurements. For example, Okkesim and Erhamza⁷ reported significant sex-based differences in mandibular ramus dimensions using CBCT. Inci et al.¹⁹ achieved high accuracy rates (51-95.6%) for sex estimation based on mandibular ramus measurements, with superior ramus height being the most discriminative parameter. Meyvaci et al.³⁰ evaluated angular mandibular parameters and reported a 71.5% accuracy rate using a discriminant function based on four angular measurements. These findings confirm the presence of sexual dimorphism in both mandibular and cranial structures among the Turkish population. However, prediction accuracy depends on the selected parameters and methodology.

In a recent meta-analysis, mandibular measurements were found to be valuable indicators for sex estimation, as males typically exhibit greater bicondylar and bigonial breadths compared to females.¹⁸ In our study, coronoid length, left condylar length, and bigonial breadth were found to be most distinctive parameters. Bicondylar and bigonial breadth were found to be sexually discriminative parameters align with the meta-analysis results. They reported a heterogeneity in the results of studies regarding the presence of sexual dimorphism in mandibular angle measurements, interestingly they reported sexual dimorphism on CBCT scans, this distinction is not evident in computed tomography scans. In our study mandibular angle was not different between males and females on CBCT scans and females had slightly higher values. While some studies have reported higher values in females,^{19,21} others suggest that it lacks consistent dimorphic patterns across populations.^{20,23} Bulut et al.³¹ found that the mandibular angle was only significantly different in older age groups (60-80 years), suggesting that age-related changes may confound its forensic utility.

In addition to sex-related differences, age was significantly correlated with certain mandibular parameters, including mandibular length, bicondylar breadth, and symphyseal height. The mandible undergoes morphological alterations in size and structure throughout human growth. Studies have demonstrated a strong association between chronological age and mandibular morphology, particularly in the ramus region.³² In a study investigating the direction of craniofacial growth from late adolescence to late adulthood, it was concluded that mandibular growth direction differed between

genders, with males exhibiting more forward rotation; this may explain why the mandibular angle tends to be lower in males.³³ In our study, although the mandibular angle showed slightly higher values in females, it did not demonstrate significant sexual dimorphism, which may partly reflect its age dependency. Therefore, while CBCT-derived mandibular measurements are highly useful for sex estimation, parameters that are susceptible to age-related changes should be interpreted with caution in forensic practice.

The integration of advanced medical imaging techniques such as CBCT into forensic science has significantly enhanced the accuracy and reliability of skeletal assessments. Compared to conventional cephalometric radiographs, CBCT offers superior resolution, three-dimensional visualization, and non-invasive measurement capabilities, reducing inter-observer variability and increasing objectivity.^{5,8} These advantages are particularly beneficial when evaluating sexually dimorphic features of the mandible.

Recent advances in AI-based approaches have substantially enhanced medical imaging, with notable implications for forensic science, including tasks such as age estimation and sex determination. In forensic contexts, accurate prediction of age and gender is essential, and deep learning offers the potential to increase both reliability and efficiency in these assessments. Recent studies support the potential of automated pipelines for forensic sex estimation. Küchler et al.¹³ demonstrated that combining mandibular and dental measurements with machine-learning algorithms achieved high predictive performance for sex determination. Similarly, a study evaluated CBCT-derived morphometric features across multiple classifiers, confirming their accuracy for sex identification.¹² More recently, Pishghadam et al.¹⁵ introduced an explainable multi-task deep learning framework applied to dental CBCT images, enabling simultaneous age estimation and sex classification with attention-based interpretability. These advances highlight that integrating AI based approaches can provide reproducible, observer-independent methods that enhance the forensic applicability of mandibular morphometry.

This study possesses several notable strengths that enhance its scientific validity and potential applicability. First, the relatively large sample size ($n=199$) contributes to the statistical power and increases the reliability of the conclusions drawn. Second, a comprehensive set of nine bilateral mandibular morphometric parameters was assessed, allowing for a multidimensional evaluation of sexual dimorphism. The use of CBCT imaging—a high-resolution, low-radiation, and non-destructive modality—offered superior anatomical detail and measurement accuracy compared to conventional radiographic techniques. Finally, the application of a broad range of statistical analyses, including GLM, t-tests, Pearson correlation, and both standard and stepwise discriminant function analysis, enriched the robustness of the findings and allowed for the development of predictive models with high classification accuracy.

The results of this study have important implications for both clinical and forensic practices. From a forensic perspective, the high accuracy of sex estimation based on CBCT-

derived mandibular measurements offers a valuable tool for identification in mass disasters, criminal investigations, or culturally sensitive contexts where autopsies are restricted. The mandible's resilience to trauma and postmortem degradation further supports its utility as a key element in forensic anthropology. Clinically, these findings may assist in designing sex-specific diagnostic, surgical, or prosthetic interventions, particularly in maxillofacial and orthodontic fields. Furthermore, the measurement protocol and discriminant function outputs of this study could serve as foundational datasets for developing automated sex estimation algorithms based on machine learning, thereby reducing operator dependency and increasing efficiency.

Future research should aim to include additional cranial and facial measurements, explore sex estimation in subadults, and validate findings in larger, multiethnic samples. Integrating artificial intelligence models—such as CNNs for direct image-based classification, U-Net variants for automated mandibular segmentation, and machine-learning classifiers (e.g., support vector machines, random forests) trained on CBCT-derived measurements—with large annotated datasets may pave the way for fully automated and standardized forensic identification systems.

Limitations

Despite its contributions, the study has several limitations. The analysis was limited to mandibular structures, excluding other potentially informative craniofacial or skeletal landmarks that may improve classification accuracy. Moreover, the retrospective study design may introduce inherent biases related to patient selection and data quality. Although the sample encompassed a wide age range, subgroup analyses by specific age cohorts were not performed. This limits the ability to comprehensively assess age-related variations in mandibular morphology, despite the observed correlations suggesting that age may act as a contributing factor. Since the primary aim of the study was to investigate sex differentiation, detailed age-stratified analyses were beyond the intended scope but should be considered in future research. Finally, the study was conducted on a single Turkish population, which may limit the generalizability of the findings to other ethnic or demographic groups.

CONCLUSION

This study demonstrated that mandibular morphometric parameters obtained from CBCT images exhibit significant sexual dimorphism and can be used effectively for sex estimation in a Turkish population. Among the evaluated measurements, coronoid and condylar lengths, mandibular length, and transverse dimensions such as bigonial and bicondylar breadths showed the highest discriminative power. The discriminant function analysis yielded a high classification accuracy, highlighting the potential of these parameters as reliable forensic indicators. Given the mandible's durability and resistance to postmortem changes, CBCT-based morphometric analysis provides a reproducible and non-invasive approach for personal identification. Future studies incorporating larger and more diverse populations, along with AI approaches—such as machine learning and

deep learning models-are encouraged to further validate and refine these findings for broader forensic and anthropological applications.

ETHICAL DECLARATIONS

Ethics Committee Approval

The study was carried out with the permission of the Süleyman Demirel University Health Sciences Ethics Committee (Date: 04.07.2025, Decision No: 35).

Informed Consent

Because the study was designed retrospectively, no written informed consent form was obtained from patients.

Referee Evaluation Process

Externally peer-reviewed.

Conflict of Interest Statement

The authors have no conflicts of interest to declare.

Financial Disclosure

The authors declared that this study has received no financial support.

Author Contributions

All of the authors declare that they have all participated in the design, execution, and analysis of the paper, and that they have approved the final version.

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